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Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry

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Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry

Abstract

In the last two decades, the auto industry has shown a steady increase of vehicle development outsourcing and a shift of both product development tasks and knowledge from car makers to suppliers. This trend has increased the interest toward product modularity as a tool to ease the integration of external sources of innovation but, interestingly enough, there is little evidence concerning the benefits of modularity in inter-firm coordination in the automotive industry. Indeed, although modularity literature considers standard interfaces one of the constitutive elements of modularity and a means for easing design outsourcing, very few studies have analysed neither the genesis nor the micro-dynamics of the interfaces definition process. In order to fill this research gap, this paper focuses on how assemblers and suppliers define the component-vehicle interfaces in component co-development projects. This study adopts a "quasi-experimental design approach" and compares two similar component co-development projects (air-conditioning systems) carried out by a Japanese first-tier supplier with two European automakers. Under the *ceteris-paribus conditions* defined by the research design, the empirical evidence derived from the analysis of the two projects shows that, differently from what modularity theory claims: a) interfaces diverge significantly in the two cases; b) the interface definition process is neither technologically determined nor the mere result of product architectural choices; c) the OEMs and the supplier's capabilities, degree of vertical integration, knowledge endowment and strategic focus drive the partitioning of the design and engineering tasks, the interfaces definition process, and the choice of the inter-firm coordination mechanisms. Furthermore, while component modularity and design outsourcing co-vary and complement each other in modularity literature, our findings suggest that they may work as substitutes and are rather difficult to combine.

Keywords: Component modularity; interfaces; auto industry; external innovation; inter-firm coordination; buyer-supplier relationships.

1. INTRODUCTION

The integration of external sources of innovation has become a problem that more and more firms need to address (Chesbrough, 2003). Inter-organizational integration mechanisms (co-located project teams, integrators, resident-engineers, collaborative technologies, IT infrastructures, etc.) are by now a classical topic in organization theory and a large body of research has analysed their ability to sustain supply relationships capable of spurring inter-firm innovation (Clark and Fujimoto, 1991; Helper and Sako, 1995). In this respect, product modularity has received much attention and has been credited of many advantages.

For example, modularity supporters claim it can improve the management and the outputs of the new product development (NPD) activities by: a) allowing firms to easily de-couple both the design and the manufacturing of the components that constitute a product; b) ensuring an easy and well performing integration of the externally supplied components into the final product architecture. Overall, modularity is believed to help firms manage outsourcing efficiently and effectively thus facilitating the integration of external sources of innovation (Baldwin and Clark, 1997, 2000; Langlois and Roberts, 1992; Sako and Murray, 1999a).

The features and advantages of product modularity have been investigated by both the managerial and engineering literatures. Industry studies show that the average degree of component modularity varies across industries (Fixson and Park, 2008; Fixon et al., 2005; Galvin and Morkel, 2001; Sturgeon, 2002). More specifically, while some industries as electronics (Baldwin and Clark, 2000; MacCormak et al., 2008) and bicycles (Galvin and Morkel, 2001) show high levels of component modularity others, as autos, stick to prevalently integral product architectures.

As far as the automotive industry is concerned, the vehicle development outsourcing trend has increased both the practitioners and scholars interest toward product modularity as a tool to ease the integration of external sources of innovation. In the last two decades, several studies have analysed how and to what extent car makers design modular cars and suppliers provide component modularity (Camuffo, 2004; Frigant and Talbot, 2005; Fourcade and Midler, 2004; Fujimoto and

Dongsheng, 2006). Interestingly, these studies offer contrasting empirical evidence on the diffusion and use of modularity in the car industry and question the benefits and feasibility of this strategy. In a recent study MacDuffie (2008) claims that cars remain overall integral products and shows that there is not a conclusive answer to key questions concerning the role of modularity in shaping the vertical contracting structure and inter-firm coordination of the auto industry. *How and to what extent does product modularity shape the allocation of design tasks and inter-firm coordination in the auto industry? Why modularity has such a limited traction in integrating external sources of innovation in the automotive industry?*

This paper intends to shed light on the above issues focusing on the vehicle-component standard interfaces definition process. In fact, even if standard interfaces are a constitutive element of modularity (Baldwin and Clark, 1997; Galvin, 1999; Hsuan, 1999; Momme et al., 2000; Sanchez and Mahoney, 1996; Ulrich, 1995), very few studies have analysed the micro and macro dynamics of their definition process. In order to fill this research gap, this paper focuses on how assemblers and suppliers define the component-vehicle interfaces in component co-development projects. We do so by analysing the process by which interfaces are defined in two projects concerning the co-development of air conditioning systems (A/C systems), which is a major vehicle component. The two projects were carried out by Denso Thermal System, a major Japanese first tier supplier, with two European carmakers. We designed our research following a "quasi-experimental" logic. We selected two similar development projects, almost identical, on the most relevant economic and technological dimensions (A/C system architecture, degree of technological complexity, vehicle market segment, degree of carry-over from previous projects, project cost, duration, and performance). This research design allowed us to observe *how* the vehicle-component interfaces emerged, to *what extent* they were standardized in the two projects, the effects of such process on task and knowledge partitioning between the car-makers and the supplier, as well as on vertical inter-firm coordination.

The study is organised as follows. The next section provides a review of the literature and presents the research questions. Section three describes the data and method. Section four and five, respectively, present and discuss the empirical findings. Section six concludes the study and offers research and managerial implications.

2. LITERATURE REVIEW

2.1. The unfulfilled promises of product modularity in the auto industry

The last two decades witnessed a steady increase of vehicle development outsourcing and a shift of both product development tasks and knowledge from carmakers to suppliers (Takeishi, 2001). This trend, paralleled by manufacturing outsourcing, led to dramatic de-verticalization processes and a re-definition of the vertical contracting structure of the auto industry towards a tiered configuration with global mega-suppliers (Sturgeon and Florida, 2004; Whitford, 2005). Therefore, as in many other sectors, to effectively integrate newly designed components inside the car system, the car makers and their suppliers have developed hand-in-glove relationships and started sharing a relevant amount of information (Clark and Fujimoto, 1991).

In this context, the reliance on modularity has been credited of many advantages. Early studies submitted that component modularity should ideally reduce the need for a tight coordination between buyer and supplier during the product development stage also in the automotive industry (Camuffo, 2004; Doran, 2004; Fixson et al., 2005; Ro et al., 2007; Doran, 2004; Sako and Murray, 1999b). As Sanchez and Mahoney (1996) and Baldwin and Clark (1997; 2000) showed in different industries, also in the automotive industry, the specifications of standardized component interfaces was credited to have the potential to create an information structure that allowed coordinating the activities as loosely coupled: the suppliers that design and produce a modular component know ex-ante the interfaces of the component to produce, this in turn reduces the information exchanges needed to design a component that fits the overall product design. Since components' design and development can be isolated and carried out separately by suppliers within a 'frozen' product architecture, the need for intense coordination is lowered. Also, standard interfaces allow increasing the firms' knowledge specialization and decoupling till labelling the modularity sourcing as black-box sourcing[1] (Lamming, 1993).

MacDuffie (2008) well summarises the theoretical and potential benefits of component modularity as regards the NPD activities inside the auto industry. First, component modularity should increase the rate of introduction of modular and incremental innovations (Henderson and Clark, 1990). Being modular products conceived as the sum of modules, separated by well defined and frozen interfaces, products can be innovated adding, up-grading, substituting, or subtracting components (Ulrich, 1995), without changes in the other product components. Second, component modularity via standard interfaces provides a form of *embedded coordination* that reduces the need of high-power integration tools to achieve coordination in development processes, thereby making possible the concurrent and autonomous development of components by *loosely coupled organization structures* (Sanchez and Mahoney, 1996). Third, the concurrent and autonomous development of components speed the throughput time of new NPD activities thus reducing the NPD costs.

Nevertheless, recent empirical evidence shows that, as concerns the automotive industry, modularity has produced disputable benefits (Fourcade and Midler, 2004; MacDuffie, 2008; Zirpoli and Becker, 2011a). A first reason for such a limited impact of modularity in the industry is pointed out by MacDuffie (2008): few cars' components are truly modular and autos are integral products. When the de-verticalization process took place inside the auto industry, while it seemed as if the auto industry would soon mimic the computer industry and converge to a modular configuration, in practice this did not happen. In fact, despite the efforts of some US and European carmakers, modularization has not been implemented successfully, with rare exceptions (Sako and Murray

[1] Here we define "black-box sourcing" as an approach in which different subjects/firms can design product's components independently from one another. A black-box approach allows developing a product's components without knowing the other components technology and working principles. Therefore, in a black-box approach not only the development activities of the diverse components are separated but even the respective knowledge domains.

1999; Sako, 2004). But it is not still clear why cars are today overall integral products despite the carmaker's interest toward modularity.

A second, and related explanation relates to the object of integration that modularity enables. Zirpoli and Becker's (2011a) empirical evidence shows that modular product design is not the most appropriate way to deal with the issue of integrating the overall vehicle *performance* (or functions): for this purpose the assessment of the reciprocal interdependencies between the performances of the different components and systems is difficult *ex ante*. As a consequence, there are intrinsic limits in the benefits of standardized interfaces as this action risks to *not* standardise the performance contribution of each single module to the whole. Standardizing interfaces does *not*, therefore, diminish reciprocal interdependencies between component- and systems-performances. Building on different evidence Zirpoli and Camuffo (2009) confirm that in the automotive industry the need for 'thick' supply relationships persists, no matter how modular components are. The reason is that product architecture is not the main determinants of task and knowledge partitioning in the observed relationships.

These contributions echo similar findings in other industries (e.g. Brusoni, 2005; Brusoni et al., 2001; Prencipe, 2000) and represent a first step in understanding how and to what extent product modularity shapes the allocation of design tasks and inter-firm coordination and why modularity might show some limited traction in coordinating the integration of external sources of innovation in the case of complex products. Notably, the *file rouge* that cut across this literature is an explicit criticism towards the over reliance of some literature on the concepts of modularity, and standard interfaces, as tools for easing inter-firm coordination.

Although modularity literature considers standard interfaces one of the constitutive elements of modularity and a means for easing design outsourcing, to date, with very few exceptions (MacCormack et al., 2010; Zirpoli and Camuffo, 2009), there is a substantial lack of studies that provide empirical evidence on the process by which standard interfaces are defined by OEMs and suppliers and how this process does, or does not, shape the way the OEM integrates external sources of innovation. The research presented in this paper represents an attempt to start filling this empirical gap. The next section reviews the literature that has dealt specifically with the issue of interfaces definitions, connects it to the modularity literature and introduces the empirical work.

2.2. The key role of interfaces standardization within product modularity

Products are complex systems in that they comprise a large number of components with many interactions between them. The scheme by which a product's functions are allocated to its components is called its "architecture" (Ulrich, 1995). Modularity refers to the way in which a product design is decomposed into different parts or modules.

Research at the crossroads of management and engineering proposes a variety of definitions of product modularity, highlighting what features may characterize a product's component as "a module" (Campagnolo and Camuffo, 2010; Gershenson et al., 2004; Fixson, 2007; Mikkola, 2006; Salvador, 2007; Ulrich, 1995). While authors vary in their definitions of modularity, they tend to agree on the concepts that lie at its heart; the notion of interdependence within modules and independence between modules. Baldwin and Clark (2000), as well as Sosa et al. (2004) argue that "modules" are characterized by independence across and interdependence within their defined boundaries. This independence is achievable through the adoption of interfaces that decouple the development and the inner working principles of a product's components.

There are different types of modularity-in-design. Ulrich and Tung (1991) propose a classification based on how the final product configuration is built. Their typology distinguishes between component-swapping, fabricate-to-fit, bus and sectional modularity, and captures different possible approaches to combining modules. Ulrich's (1995) typology relies on the nature of the interfaces among components as the classification criterion and distinguishes between slot, sectional and bus modularity. Salvador et al. (2002) complement these typologies introducing the notion of combinatorial modularity as a sub-type of slot modularity and contrasting it with component swapping modularity. In combinatorial modularity each product component is a variant within a component family and each component family interacts with a subset of other component families. The interactions are ensured by standardized interfaces that may differ depending on the combination of families they connect but are independent of the component variant chosen, so that "all component families are allowed to vary while the interface between specific pairs of component families is standardized" (Salvador et al., 2002: 571).

Despite the differences in approaches, definitions and emphasis, scholars converge in identifying three main features of modules: they are separable from the rest of the product; they are isolable as self-contained, semi-autonomous chunks; and they are re-combinable with other components. Separability, isolability, and re-combinability are properties deriving from the way functions are mapped onto the components and from how components interact, i.e. from their interfaces.

Ideally, a perfectly modular product is made of components that perform entirely one or few functions (1:1 component/function mapping), with interfaces among them well known, defined, and codified (Ulrich, 1995). If these interfaces –i.e. the communication protocols among components- are widely diffused within a given industry, these components have open standard interfaces. However, if the protocols are designed specifically to suit a certain firm's requirements, i.e. they are firm specific, these protocols are closed and non-standard -unless we consider closed interfaces as proprietary standards used by a single firm or a specific network of firms (Fine et al., 2005). Interestingly, modular products are characterized by standard interfaces among components, but the other product's features and attributes –including technologies- may change. Thus, a modular component is not necessarily standard.

Therefore, since the modularity literature converges in identifying standard interfaces as a core technical attribute of a module (Campagnolo and Camuffo, 2010; Fixson et al., 2005; Salvador, 2007; Ulrich, 1995), investigating the nature of the interfaces definition process is critical to understand the connection between modularity and component development outsourcing and the integration of external sources of innovation. Within the modularity literature, Baldwin and Clark

(1997) were the first to underline that standard interfaces allow modules to be designed independently and, consequently, "mixed and matched" to create a complete product-system. Hsuan (1999) and Momme et al. (2000) also observe that, in modular design, it is standard interfaces that allow for a range of variations in components to be combined in a product architecture. Salvador (2007) goes even further with his "interfaces standardization approach", describing how the view of product modularity as interfaces standardization originated in the computer industry, was developed by the economic literature during the '80s, and became widespread in the strategic management literature with Garud and Kumaraswamy (1993). Finally, Pimmler and Eppinger (1994) emphasised the role of interfaces in the engineering literature, creating specific tools to analyse them, such as the Design Structure Matrix (DSM).

Overall, since interfaces are the coupling protocols among components that ensure that they will work together well, if interfaces are defined *ex-ante* and stable (i.e. trough out the life of a project), the development of each component can be de-coupled and conducted independently. Consequently, standard interfaces should ease the outsourcing of NPD activities to suppliers, favouring vertical disintegration (Langlois and Roberts, 1992).

Interfaces definition can be ensured in three ways. First, interfaces may be defined adopting open standard interfaces, i.e. adopting the communication protocols among components widely diffused within a given industry (Fine, 1995). Second, interfaces may be close standard i.e. a firm designs communication protocols among components that, although firm specific, represent internal standard requirements that are replicated across products and projects (Takeishi and Fujimoto, 2003). Third, interfaces may be stable, i.e. well defined but not necessarily standard (neither open nor close). In this case they are firm specific, newly designed to suit the need of a specific development project, but frozen once the project starts (Christensen et al., 2002).

This study, though focusing on how components interact (i.e. their interfaces), also considers components' separability, isolability, and recombinability as properties that derive on how functions are mapped onto components.

3. DATA AND METHOD

Our research questions seek to shed light on the role of modularity in integrating external sources of innovation and on the reasons of its limited traction inside the automotive industry, focusing on the macro and micro dynamics of the interfaces definition process during the NPD activities. Indeed, we opted for a qualitative method, the multiple case study research design, which is considered an appropriate way to describe and explore new phenomena and build testable theoretical propositions (Eisenhardt, 1989; Yin, 1994; Handfield and Melnyk, 1998; Meredith, 1998). In order to observe the actual role, strengths and weaknesses of component modularity we built our sample following the principles of experimentation. More specifically, we adopted a "quasi-experimental design" approach (Romanelli and Tushman, 1986). After selecting one of the most modular components in the car industry, the Air Conditioning system (A/C system) (Fourcade and Midler, 2004), we built a research setting in which, keeping constant the variables related to product architecture and technology, and being other things equal, we could observe how and if task and knowledge partitioning and the inter-organizational coordination mechanisms vary in the two observed projects.

In order to do so, we followed a three-step process. First, we decided what component/system to analyse. Second, we defined under which conditions two development projects would be comparable. Finally, we sought and found the field setting in which to apply our research design.

3.1. Object of analysis

The choice of the component/system to analyse was critical to make the analysis meaningful and the cross-OEMs's comparison fruitful. Following Takeishi and Fujimoto's (2003) observation that a vehicle can be decomposed using different levels of granularity (from a single component such as a brake calliper to a front module made of many heterogeneous components), we opted for a relatively aggregate level of analysis and chose to analyze a complex component, i.e. a system made of a significant number of sub-components involving heterogeneous technologies. Indeed, in the development of such systems, car makers usually involve several suppliers and face challenging inter-firm coordination problems. At this aggregate level, practitioners and scholars tend to converge in maintaining that a vehicle is made of a limited number of components/systems such as the occupant safety system, the brake system, the power train, the heat, ventilation and air conditioning, the doors, the cockpit, the front end, etc.

With our research questions in mind we selected as object of the analysis the Air Conditioning System (A/C System). The air conditioning system has a stable architecture and a mature technological content and can be characterized as a relatively modular, fully "outsourceable" vehicle component (Doran, 2004; Fuorcade and Midler, 2004).

Our preliminary interviewees confirmed that A/C system interfaces with the other vehicle components can be clearly defined and codified by OEMs as regards performance requirements and technical specifications. In fact, when we approached the designated A/C supplier, Denso Thermal System (henceforth DNTS), a major global supplier of thermal systems for the automotive industry, we preliminarily addressed the issue of the A/C system architecture and its implications for buyer-supplier coordination. We first analyzed if and to what extent the A/C system could be considered "modular" and then what modularity meant in practice, what use of this conceptual tool was made and if modularization, as defined in product design literature, had represented a significant trend in auto A/C systems' development. During these preliminary interviews, DNTS's R&D chief confirmed that among the various main systems of a car, the A/C system could be considered among the most fully "outsourceable" and loosely coupled with the rest of the vehicle.

3.2. Co-development projects' selection

The second step was to set the context for our comparative analysis. We selected, with the help of DNTS's R&D chief, two distinct development projects, started approximately at the same time, in which DNTS was developing, respectively, the A/C system for two car models at that time being engineered by two competing OEMs (ALPHA and BETA). Both A/C systems were targeted to vehicles of the same market segment, and were characterized by similar technology and degree of novelty. The two projects were typical, i.e. a good proxy for the usual way DNTS and its customers co-develop an A/C system. With these criteria in mind, we selected the following projects:

- Project-A refers to the development of the A/C system for a new ALPHA light commercial vehicle with a passengers use variant. The project was launched in 2003 as a derivative of an existing product platform. Currently, the previous project and Project-A represent about 2% of the total DNTS's revenues and 40% of the DNTS's volumes with ALPHA.
- Project-B refers to the development of the A/C system for a new BETA light commercial vehicle with a passengers use variant and a direct competitor of the above described Alpha model. Also this project was launched in 2003 and was derived from an existing A/C platform. DNTS was the only supplier for the analyzed project. Currently, Project-B accounts for approximately 6% of DNTS's total revenues, while it represents about 90% of DNTS's business with BETA.

Overall, our research design created the conditions for a meaningful analysis of cross-OEM variation as it allows to compare the two OEMs' patterns of coordination referring to two co-design projects that share the same supplier (DNTS), the same modular component (A/C system), a similar component architecture[2] and technological complexity, a similar project degree of novelty, carryover, year of start, etc. and similar project performance targets.

As regards data sources and gathering, we analyzed company documents and conducted several rounds of structured and semi-structured interviews between November 2007 and April 2008. An additional round of interviews and meeting was conducted in May 2009. Table 1 lists the managers we interviewed and the duration of the interviews. We decided to interview both the projects 'account managers' (responsible for the commercial relationship with the OEM from the

[2] Today there are two main A/C systems architectures: centered and semi-centered. Both projects selected employed a centered architecture.

pre-offer phase until the end of the project) and the ‘project managers’ (responsible for component or system development). As Table 1 shows we did not interview managers at the car makers. In fact, as we were interested in triangulating data on two projects, only DNTS’ managers could provide us the comparative perspective we needed.

Insert Table 1 approximately here

4. FINDINGS

In this section, after illustrating the genesis of DNTS’s relationships with ALPHA and BETA, we break down the presentation of our findings articulating them into four sub-sections: the first reports on how design and engineering tasks were partitioned between DNTS and the carmakers in the two projects; the second on the implications of between-firm task partitioning on the architecture of the A/C system; the third on the performances of the two projects; and the fourth on the cross-relation differences about the applied inter-firm coordination tools. During our fieldwork the interviewees confirmed that the two projects were fully representative of the “usual” division of labour and coordination mechanisms employed in the relationship between DNTS and the two analyzed car makers.

4.1. The genesis of DNTS’s relationships with ALPHA and BETA

DNTS was established in 1987 as Magneti Marelli Climatizzazione. In 1990 a joint venture was set up with the Japanese Denso Corporation (Nippondenso, at the time), world leader in the industry, leading the company into a phase of rapid growth of investments in R&D structures, new production facilities, technologies and competencies, and a stronger presence in the European Market. In 2001 Denso acquired full ownership of the company that adopted the name Denso Thermal Systems S.p.A. Nowadays, DNTS designs, develops, manufactures and sells air-conditioning systems, engine cooling systems, heat exchangers, radiators and compressors for cars, commercial and industrial vehicles and also for tractors, earth moving machinery, buses etc. It is also active in designing and assembling integrated cockpit and front-end modules for cars. DNTS supplies all the major automotive manufacturers in Europe and South America. In the following paragraphs we present in detail the genesis of the two projects analysed.

Project A was developed by DNTS for ALPHA in 2003 from an existing product platform. Denso was the only supplier for both projects. ALPHA launched the Request for Quotation (RFQ) of project A in 2003 and a handful of suppliers (Behr, Valeo, and DNTS) replied to the request within 3-4 months. According to the sales & marketing manager that had the commercial responsibility of the project, DNTS acquired the business for three main reasons. First, ALPHA positively evaluated the type of mixture air system proposed by DNTS. Second, the prototype developed by DNTS had the highest performance levels. Third, DNTS could leverage the fact of being co-located with ALPHA, being the only supplier that had decided to open a new production site closed-by ALPHA's assembly plant. In this phase ALPHA did not fix a target price and DNTS suggested its own price. DNTS could offer a particularly interesting price also because of the cost advantage due to production co-location. DNTS won the RFQ in 2003, and was selected by ALPHA 48 months before the expected production start and ramp-up.

Project B was developed by DNTS for BETA. DNTS was the only supplier for the analyzed project. The project was derived from a pre-existing platform developed by DNTS's competitor. In 2003 BETA launched the RFI (Request for Information). As usual, during this step BETA involved five competing suppliers (DNTS, Valeo, Behr, Delphi, Carlsonic) providing them with business information among which volume forecast for the A/C system. The suppliers were asked to suggest the best technical solution and the price. Once this phase was completed, BETA chose the best technical solution and launched the RFQ. DNTS won the RFQ at the end of 2004. The development of the A/C system took about two years. The BETA's production started in 2007. According to the sales and marketing manager that had the responsibility of the project, DNTS was able to acquire the above business thanks to its superior technical knowledge, its cooperative approach, and its price. He also told that, although price was an important variable, only suppliers that had previously demonstrated their technical capabilities could participate to the RFQ. In fact, BETA employs such a complex supplier's evaluation system and certification procedure that: "*to be a BETA's supplier you need to pass a strict exam every 5-6 years. Therefore BETA assumes that you are able to develop the A/C system required and this is why, given that, they push price competition*".

Overall, DNTS's relationships with ALPHA and BETA are long-lasting, collaborative, and solidly grounded on the technical knowledge and price competitiveness. Consequently, DNTS knows well both car-makers, their procedures and their technical competences.

4.2 Design and engineering task partitioning in Project-A and Project-B

4.2.2 Interface definition

This section reports in detail how DNTS, ALPHA and BETA respectively partition their design and engineering tasks. In line with our research questions, we start describing how the two carmakers and DNTS set the interfaces between the A/C system and other vehicle systems with which the air conditioning interacts. For each firm, we gathered the data using a table, which represents a modified version of the Design Structure Matrix (DSM), a tool specifically suggested by the literature to analyse interfaces (Pimmler and Eppinger, 1994). The table we used is structured as follows: the car's components with which the A/C system interacts are reported in the rows, while columns contain the indication of the type of interfaces that exist between the A/C system and the vehicle components (listed in rows). Following Pimmler and Eppinger (1994), we analyzed four types of interactions between the A/C system and the car's components: a) spatial (e.g. physical adjacency, alignment, orientation); b) energetic (e.g. heat, vibration, electricity); c) material (e.g. air, oil, fluids, flows); and d) informative (e.g. signals, controls transfers). Indeed, we analysed the interfaces as follows. First, for each component with which the A/C system interacts we identified the kinds of interaction (spatial, material, energetic, informative). Second, for each kind of interaction we checked if it represents an open standard (O-S) (i.e. the interface is a standard used by companies operating in the industry), or closed (C-S) (i.e. the interface is a standard within the OEM projects), or non standard (N-S) interface. Finally, either if the interface was standard or not we checked for its stability over time (i.e. across the project life-cycle) employing a 1-5 point scale where 5 stands for "frozen interface from the start of the project" and 1 stands for "unstable interface that often changes during the project"[3]. In order to reduce the subjectivity of the interfaces characterization and to ensure the results comparability, we asked to the chiefs of Project-A and Project-B to fill in the tables under our supervision so that the interfaces could be evaluated consistently in the two projects. Also, once the tables were compiled, we organized a meeting with the two chiefs and DNTS's R&D Chief, to compare the tables and, eventually, to fine tune them. This meeting allowed to taking into consideration the different perceptions the two project managers might have about the use of the applied metrics.

This process ended up with the final release of the two tables (see Table 2 and Table 3) that summarise and compare the interfaces between the two projects. Each table took about two hours to be completed and other 2 hours to be adjusted in the final meeting.

Project-A

Table 2 reports the results obtained for Project A's interfaces analysis.

Insert Table 2 about here

Table 2 shows that *all* the interfaces analysed were frozen from the beginning of the project and that 10 up to 18 interfaces were either open or closed standard. Our interviewees were unanimous in stating that ALPHA fixed the product's architecture and the interfaces in great detail. All the managers we interviewed stressed ALPHA's ability in well defining the specifics early in

[3] Usually, the stability requirement is captured through standardization. Nevertheless, it may happen that even an interface never employed before (i.e. non standard) could be designed by the car maker and frozen at the beginning of the project. In this case we have an interface that, as the standard interfaces, is stable and can ease the integration of external sources of innovation reducing the project's uncertainty. But it is also possible that an OEM adopts a closed set of standards for a specific interface and, after committing to one of these interfaces it later decides to replace this interface with another belonging to the same set. In this case we would observe a standard interface that does not imply the benefits of the ex-ante defined, "frozen", interfaces.

the project (interfaces, functions, performance levels, etc.). This data is confirmed by the Chief of Project-A who reported to us: "*For ALPHA the specifics remain stable after the avant phase*" (48 months before the ramp up) and "*ALPHA is a strict OEM that does not change its specifics: once the specifics are set, these do not change for all the suppliers involved in the car development*". Notably, the managers claimed that the specifics constitute one of the main coordination tools used by ALPHA. In fact, the R&D chief of the project explained to us that "*ALPHA has a main set of specifics for the A/C system that is articulated in dossiers, one for each component. The main set of specifics contains the general requirements and standards for the system. Indeed, the architecture is completely defined ex-ante by ALPHA while the supplier has the task to design and engineer most of the inner components of the A/C system, respecting the detailed specifics given by ALPHA*". The interfaces, defined within the main set of specifics, are well specified also because ALPHA first designs the other vehicle components and then the A/C system. Of course, DNTS's managers noted that the higher the numbers of frozen interfaces the lower the design's degrees of freedom left to DNTS.

Moreover, ALPHA defines some A/C system's inner components. According to the Chief of Project-A "*ALPHA defines these components to better control the A/C system's architecture and to control those components whose performance has the higher impact on the passengers' comfort*". Notably, the interviewee stressed that "*ALAPHA does not define these components only to achieve higher levels of commonality among different platforms, […] Interfaces standardization is not aimed at improving the modularity level of the A/C system per se but as a mean to better control the overall A/C system performance*".

ALPHA's ability in defining the A/C system architecture and specifics was fully acknowledged by DNTS. The engineering managers reported to us that when they tested the A/C system on the car the results were totally positive. DNTS's managers also said that, during Project-A, they were highly confident that the test results would have been good as "*their [ALPHA's] specifics were clear and did not change. Moreover, we strictly followed their specifics*". ALPHA's ability in setting and standardize the specifics is also well captured by the R&D chief of the project's observation that "*ALPHA on the same platform has several groups made by different suppliers that are interchangeable even if the systems* (i.e. the A/C systems) *are not the same. This is because ALPHA well defines all the specifics that are available to all the suppliers*".

Figure 1 sketches ALPHA's approach in defining the A/C system architecture.

Insert Figure 1 approximately here

The main rectangle delimited by the green frame represents the A/C system interfaces, the small rectangles represent the inner A/C system sub-components, and the oval the overall performance parameters and engineering solutions. Figure 1 shows that ALPHA fully specified all the interfaces (the green zone), some active components (the blue boxes inside the A/C system boundaries), and the performance parameters as well as the engineering solutions (the yellow zones). The white zones were those fully managed by DNTS.

Project-B

Table 3, which refers to the analysis of Project-B interfaces, shows a rather different picture.

Insert Table 3 about here

Table 3 shows that 20 up to 23 interfaces were either closed or open standard. But, interestingly enough, 12 up to 23 interfaces had a stability level equal or lower than 3 and 8 interfaces were standard with a stability score equal or lower than 3. As previously explained, an interface is standard but unstable when substitutes another standard interface during the project development. According to Project-B's R&D chief, during the project, BETA allows all components suppliers suggesting components interfaces changes. This data is consistent with the information that "*BETA started Project-B with hypotheses that had to be defined in more details* *with the suppliers involvement*". Indeed, during Project-B the initial A/C system architecture evolved, and DNTS was involved in these architectural changes. This explains why Project B interfaces were unstable.

Moreover, Project BETA R&D chiefs explained that the components, with which the A/C system interacts, as the flame damper, are strictly related to the car's design and style and are modified in every car-model. Consequently, "*every time the cockpit supplier suggests changes in the cockpit style, these require changes in the A/C system*". Indeed, A/C system's frozen interfaces may negatively affect the cockpit design innovativeness. Overall, DNTS people agreed that a black-box approach was not feasible in BETA: "*it would have been too risky to develop the A/C system as a black box. … Only through opening the black-box DNTS can help BETA evaluate and decide exactly the consequences of the BETA's requirements: the black-box approach does not allow BETA understanding the impact that some changes required at the vehicle system level might have on the overall A/C performance, while an intense information sharing helps BETA in better defining the final A/C system's configuration*".

The manager stressed the evidence that BETA and DNTS have different bodies of knowledge, but since they do not develop isolated tasks, they need to integrate their knowledge domains to effectively integrate the car's components.

Figure 2 sketches the BETA approach in defining the A/C system architecture. The main rectangle delimited by the green frame represents the A/C system interfaces, the small rectangles represent the inner A/C system sub-components, and the oval the overall engineering solutions. BETA sets the A/C system main concept and architecture but allow, and in some cases ask for, DNTS's suggestions about how to improve the system even at the performance and architectural level (the yellow zone). Also, BETA co-develops the interfaces with DNTS (the green zone) and does not define the A/C system inner components (there is no blue box inside the A/C system boundaries). The white zones are those fully managed by DNTS.

Insert Figure 2 approximately here

4.2.2 Functional isolation

After the interfaces analysis, we studied the two A/C systems' level of functional isolation directly interviewing the R&D chiefs of the ALPHA and BETA projects. Our interviews highlighted that – in both cases - the interfaces standardization was not coupled with a complete functional isolation though and that both carmakers were aware of the need of addressing functional interdependences between the A/C system and the rest of the vehicle.

On one hand the R&D chief of Project-A explained that "*the A/C system shares several functions with other components, and the integration issues are all managed by ALPHA that defines the A/C system performances and interfaces knowing the interdependencies with the other car components.* […] *When the OEM defines the specifics for the compressor, it knows that the compressor interacts with the A/C system, therefore sets the right specifications for both the A/C system and the compressor*". On the other, the R&D chief of Project-B explained that BETA managed the A/C system integration into the vehicle relying on DNTS competences. DNTS helped BETA in understanding how the A/C system would have performed given the specifics of the components with which the A/C system shares its functions.

Hence, our data highlights noteworthy differences between APLHA and BETA. ALPHA's in depth technological knowledge of the A/C system enabled the carmaker to manage all the key interdependencies. The R&D chief of Project-A stressed that ALPHA's level of architectural knowledge was higher than DNTS's one while ALPHA's knowledge about the A/C system's structural and functional coordination with the main components of the A/C System was similar to DNTS's. The Project-A sales & marketing manager explained that ALPHA deepen and maintain its technical knowledge directly cooperating with some second tier suppliers, especially to develop new components: "*ALPHA is integrating internal competences till being able to develop the components inside the A/C system*". "*They are increasing their integration level to be more competent and competitive, and they have the resources to do it.*" Back to the results showed in Table 2, DNTS interviewees told us that it was due to its technical knowledge that ALPHA was able to define all the A/C system interfaces so neatly. ALPHA's high competences on the A/C system technology put the company in the position of designing interfaces between the A/C system and the rest of the vehicle and, consequently, to address the most of the A/C system's functional interdependences upfront. BETA, vice versa, knowing that it lacked the necessary component specific knowledge for developing technical specifications and addressing functional interdependencies upfront, hinged on fluid interfaces and on a higher contribution of DNTS in the definition of the A/C system components.

We also took the opportunity to ask DNTS managers, on the basis of their experience, knowledge of ALPHA and BETA, and of the industry, what were the main determinants of such different A/C systems co-development approaches between ALPHA and BETA. The explanation we were provided goes back to the priority attached by ALPHA and BETA to the A/C system performance. While ALPHA explicitly considers the A/C system performance a key feature of its vehicles, which its customers perceive as a distinctive characteristic of their brands, BETA, historically, does not put such an emphasis on the A/C system performance. This can be a reasonable explanation of why ALPHA has kept under stronger control the A/C system technology. In fact, the managers also clarified that ALPHA pursues modularity, defined as interfaces standardization, mainly to increase its component control.

4.3. Project performance

During our interviews, we gathered DNTS managers' evaluations of Project-A and Project-B outcomes, which were similarly good. The interviewees were satisfied with both the A/C systems, and the project development targets (time, cost, quality) were met in both cases. In absolute terms, Project-A had more ambitious technical specifications (perceived quality of air conditioning by the final customer) but, overall, the performances of the two projects were definitely similar.

Also DNTS considered ALPHA's and BETA's approaches to knowledge and architectural management as consistent because they were well integrated. ALPHA couples high level of component specific knowledge with the ex-ante definition of the A/C system architecture, while BETA couples lower levels of component specific knowledge with a higher reliance on the supplier's competences to modify and adjust the A/C system architecture. As the concept of consistency ran the risk to remain vague, we also asked DNTS managers for a counter example (inconsistency). For example, DNTS considered the OEM GAMMA's approach rather inconsistent because GAMMA wanted to define upfront all the interfaces but it lacks the know-how. Thus, this approach created a lot of problems for DNTS when working with those interfaces that inevitably had to change when unexpected trade-offs came out and DNTS had to do a lot of re-design. The project was late and more expensive than expected.

Finally, we explicitly asked DNTS engineers their perception about modularity, what they meant by "modularity" and what they expected to gain from a modular approach. They told us that modular designs would greatly reduce the necessity to interact with clients because in case of modular designs the car maker would define the specifics, and the suppliers might interpret these autonomously. Particularly, DNTS views modularity as a property that gives to the OEM the task to design the interfaces and the performances, while it leaves to the supplier the freedom to decide how to meet the performance targets. The R&D chief of project ALPHA said, "*the car maker should define the A/C system functions and the performances leaving us the possibility to find the best technical solution*". But when we asked to refer back to the "real world" practice we were told that "*nobody* [in the auto industry] *has this approach. I believe that modularity is mainly diffused in the electronic industry but in our industry we have not already found the right level to have true black boxes because OEMs need more experience. ALPHA is near the modularity approach but they are intrusive, they should make a step back…. An OEM needs several competences to modularise a system… ALPHA, for example, has a modular approach in defining the interfaces but, to fix the product architecture, their specifics go inside the A/C system*".

The R&D chief when solicited on this point acknowledged that "*product modularity might allow employing a pure black-box approach but product modularization requires a high knowledge about the components to modularise"*. Consequently, we asked whether Denso preferred an OEM that defines the architecture and the specifics leaving the supplier the freedom to develop the component in a black-box fashion, or if it prefers an approach such as that of ALPHA. "*Definitively the first*", said the R&D chief, because a black-box approach leaves more space to the supplier. The manager specified that ALPHA by providing the specifics for inner A/C components limited the DNTS's contribution to innovation. On the other hand, the same managers admitted that ALPHA's clear and stable specifics were supportive to DNTS's design and engineering tasks. Overall, DNTS's managers acknowledged that during the project they had many opportunities for learning from ALPHA but in many respect they preferred BETA's approach.

4.4. Inter-firm coordination mechanisms

ALPHA and BETA used two completely different task and knowledge partitioning schemes mirrored by a fundamental divergence in how the interfaces between the A/C system and the rest of the carmakers' systems were defined and set. This section reports on the differences between ALPHA and BETA as far as the inter-firm information sharing is concerned.

As seen, ALPHA provided to DNTS detailed and stable definition of specifications and interfaces. Contrary to what, following mainstream modularity literature, we had initially assumed, this fact did not reduce the need for intense communication during the project. Rather, the evidence gathered in our interviews shows that the Project-A required intense information sharing, both formal and informal. The formal information exchange took place through a monthly meeting to planning the activities, and through two other by weekly meetings aimed to solving technical issues. Moreover, the DNTS's project and area chief engineers kept systematically in touch via e-mail or telephone calls with the corresponding ALPHA chiefs. These interactions were more frequent (daily interactions) and intense during the concept development and the preliminary design phases, while they were less frequent after that. The daily contacts usually aimed at solving problems that might stop the project. In fact, even if ALPHA well defines the interfaces and the specifics these do not ex-ante resolve all the interdependencies between the A/C system and the car. In this respect, the engineering manager said: "*We contact ALPHA to verify to have correctly understood their requirements or if we need their help. The goal is to do not stop the project development till the next meeting*".

Moreover, DNTS co-located the design and engineering team close to the main ALPHA location. DNTS rented a space and permanently staffed two engineers. In fact, despite the scheduled monthly meetings, frequent telephone calls, detailed interfaces definition and contractual agreements, DNTS's managers highlighted the fact that face to face communication was unavoidable: "*when Project-A was launched, we rented a space near ALPHA to be able to meet the client on a daily basis. The "human interfaces" consisted of two engineers coordinated by the area-chief*".

As far as Project-B and the relationship between DNTS and BETA are concerned, it clearly emerged that BETA co-developed the A/C system with DNTS and that heavily delegated design and engineering tasks to DNTS. The interviews confirmed that the co-development was not aimed at increasing BETA's knowledge about the A/C system, but at improving the NPD efficiency. As seen above, BETA did not heavily invest in the A/C system's knowledge and this had noteworthy consequences on how BETA managed the relationship with DNTS. As opposed to ALPHA, in fact, BETA cooperated with DNTS without sharing the same knowledge base concerning the A/C system. To do so BETA has set up a sophisticated reporting system that stores all relevant information concerning the cost of the components and the defects that the A/C systems reported on the market. The cross comparison of cost details and technical and functional problems allowed BETA to guide DNTS's choices without an in depth technical knowledge about the A/C system's inner components. BETA was known for having rigid systems and procedures to analyze the costs of the A/C system's components and asked many details about the costs of the components that

DNTS purchased. In this respect, BETA required ad hoc meetings to analyze the components chosen by DNTS, and sometimes imposed restrictions about the second tier suppliers and also preferences about their nationality.

Moreover, often DNTS managers stressed BETA's emphasis on the codification of co-development practices into standard procedures: "*every day there might be component innovations but every activity in the development process is totally routinized*". DNTS managers, in fact, emphasized that BETA had a very structured and rigorous procedure to manage its relationships with suppliers. BETA controlled the project status through a procedure made of five steps and a series of detailed milestones and required monthly meetings plus others appointments. BETA had a specialist for each project milestone. Moreover, BETA had several inspectors that supervised DNTS's activities and progresses. DNTS believes that these structured procedures did not always favour a robust engineering approach to problem solving. The true value-added of each milestone "*often depends on the specific person that manages the procedure's step*". The heavy use of procedures at times made the process bureaucratic, hindering project's advancements: "*they* [BETA engineers] *are good technicians but due to too many procedures sometimes risk stopping the project*". Overall, intense communication and frequent information sharing in all the available forms were a standard practice.

5. DATA INTERPRETATION AND DISCUSSION

Our description of the two projects shows a nuanced picture of how interfaces are defined, what shapes the division of development tasks, what drives knowledge partitioning between OEMs and suppliers and the coordination mechanisms at work. We found that the same A/C system (same product, same architecture, same complexity, similar vehicles targeted to the same market segment) was co-developed according to a different conceptual definition of the interfaces and employing different organizational solutions.

We observed that the two A/C systems, despite the similarities in terms of characteristics and performance, were developed by DNTS on the basis of interfaces that were defined by ALPHA and BETA in two substantially different ways. The decision to rely on stable and detailed interfaces (i.e. the ALPHA's approach) vs. fluid and changing ones (i.e. the BETA's approach) was not linked to intrinsic characteristics of the system under development, but derived from deliberate choices of the OEMs. Such choices, in turn, were grounded on the amount of component specific knowledge owned by the OEM and its current involvement in component design (i.e. vertical scope).

ALPHA designs stable and detailed interfaces. According to our company informants this approach worked because ALPHA had developed an in-depth knowledge of the A/C system architecture and components. This seems to point to the fact that a better and more effective definition of standard and stable interfaces is coupled with the OEM's vertical scope (i.e. the OEM holds component specific knowledge). The main drawback of the ALPHA approach was the impossibility to tap into the supplier's knowledge because of the limited supplier's freedom to suggest new and original architectural solutions. Also, DNTS's engineers claimed that interfaces standardization did not eliminate the need for frequent and intense information sharing due to the existence of complex functional interdependencies between the A/C system and other vehicle components: ALPHA's interfaces standardization level is high but, from an architectural perspective, did not manage to achieve a complete functional isolation (i.e. some functions of the A/C system remain shared with other vehicle components). Consequently, ALPHA, in order to control some of the residual functional interactions, had to be involved in the definition of some A/C system's inner components becoming "*intrusive*".

In the second case, BETA provided some directions regarding the interfaces between the system and the rest of the vehicle in a black box sourcing fashion, i.e. without specifying the A/C system architecture and the inner components features. However, since the OEM knew little about the interdependences and interactions between the components within the system and the rest of the vehicle, it had to be prepared to revise and adjust systematically the A/C system architecture and components features through intense mutual adjustment and information sharing with DNTS, during the project. According to DNTS engineers, this approach increased the possibility to introduce important innovations and improvements. DNTS had the possibility to suggest both innovations at the A/C system's inner components level as well as at the system interfaces level. But this approach also increased the project instability. In fact BETA allowed DENSO, as well as all those suppliers that produce vehicle subsystems that interact with the A/C system, to suggest changes in the subsystems interfaces during the project development.

Overall, the "dispute resolution styles" (Sabel et al., 2009) characterizing the relationships between DNTS and the two carmakers were not determined by the nature of the A/C system interfaces but followed as a natural consequence of the OEMs capabilities, level of vertical integration, and knowledge endowment.

While BETA tried to compensate its lack of component knowledge with an intense mutual adjustment and information sharing with DNTS during the project and using more sophisticated and structured inter-organizational procedures, ALPHA, being more in control of the technical interdependences, relied more on standard and stable interfaces that were complemented with a high information sharing but with less formal coordination.

As seen, both relationships were considered by DNTS as cooperative and successful. DNTS's managers used the term "consistent" to describe BETA and ALPHA's behaviour. ALPHA and BETA were considered as consistent by DNTS because their strategic approaches, knowledge endowments, capabilities and organizational structures are well integrated. In other words, OEM's strategy defines the knowledge endowment, which drives the organization of the vertical supply relationships.

Our cases, describing how modularity is achieved, offer new insides on the role of modularity in integrating external sources of innovation and, also, an intuition of why, today, cars are still integral products (MacDuffie, 2010). While the modularity literature builds on Sanchez and Mahoney's hypothesis (1996) that modular products are developed by loosely coupled organizations, we found that the OEM's strategy drives the investments in the A/C system knowledge that determine how NPD activities are managed. Sanchez and Mahoney (1996) wrote 'although organisations ostensibly design products, it can also be argued that products design organisations'. Our cases support the proposition that firm's strategic orientation and the level of vertical integration design products, and that modular design does not substitute high-power organization tools.

Standard or well defined interfaces are a coordination tool, but they neither eliminate the need of high powered integration tools nor shape the allocation of NPD activities- i.e. the "mirroring hypothesis" (Colfer, 2007) does not hold in the analyzed cases. Also, standard and stable interfaces do no lead to the *black-box* sourcing. What eases buyer-supplier coordination through interfaces stability is the level of knowledge held by the OEM and its ability to predict the technical interdependences characterizing the design over the life of the project (as the DNTS-ALPHA case shows). As Prencipe (2000) argued studying the aircraft engine control system, manufacturers need a deep understanding of components' inner functioning to specify, assess, test and integrate components externally supplied. The OEM's lack of component specific knowledge prevents the OEM from being able to envision and address upfront all the possible coupling problems. Cars components share a number of interfaces that require specific knowledge investments to be managed. These findings, thus, advance to those literature that question the possibility to encapsulate OEMs' components knowledge inside standard interfaces because firms' knowledge have to necessary span these boundaries (Brusoni, 2005; Prencipe 2001; Steinmueller, 2005; Zirpoli and Becker, 2011a) and only carmakers that know more than they do can achieve higher modularity levels (Brusoni, 2005; Camuffo and Zirpoli, 2009).

Our findings also support those literature that question the role of modularity inside the car industry (Camuffo, 2004; Fourcade and Midler, 2004; MacDuffie, 2008). Our data suggest that cars are complex systems that are not nearly-decomposable in nature (Simon, 1962): the A/C system, one of the most modular car's component, shares a number of interfaces and functions with other subsystems. This point to the many organizational challenges and costs of modularizing such complex products (Ethiraj, 2007; Zirpoli and Becker, 2011b). As Ethiraj and Levinthal (2004) pointed out, whether and how good modular designs may be achieved in the face of complexity is an important question. Our cases suggest that component vehicle modularity, defined as the use of ex-ante defined frozen interfaces, can be achieved only *if* the OEM has a strategic interest in controlling the component performance *via* direct and intense investments in the component specific knowledge.

6. CONCLUSIONS

In this study we analysed two cases of integration of external sources of innovation focusing on the dynamic process of components' interfaces definition (Baldwin, 2007; Sosa, et al., 2004). Under the *ceteris paribus* condition defined by the quasi experimental design approach, our results show that interfaces diverge significantly in the two cases and that their definition process is neither technologically determined nor the mere result of product architectural choices. In both cases, the OEMs and the supplier's capabilities, degree of vertical integration, knowledge endowment and strategic focus drive the partitioning of the design and engineering tasks, the interfaces definition process, and the choice of the inter-firm coordination mechanisms.

Our findings imply that standard or well defined interfaces, although representing a useful coordination tool (Baldwin and Clark, 2000; Sanchez and Mahoney, 1996), neither substitute high powered integration tools nor fully shape the allocations of NPD activities across firms. This is consistent with the outstanding mixed evidence about the "mirroring hypothesis" (Colfer and Baldwin, 2010), and with the idea that the automobiles are too complex a product and that the auto industry is too complex a sector for modularity to be effective as a functional equivalent of high-powered inter-firm coordination mechanisms (Cabigiosu and Camuffo, 2011; MacDuffie, 2008; Zirpoli and Becker, 2011a, b).

Moreover, as far as the interfaces definition is concerned, we observed that standard and stable interfaces do no lead to the *black-box* sourcing approach modularity theory would predict, i.e. we observe neither a clear cut partitioning of task and knowledge between buyer and supplier, nor a substantial decoupling of design and engineering activities across them. Paradoxically, it was the more vertically integrated firm that relied more heavily on vehicle-component standard interfaces. While component modularity and design outsourcing co-vary and complement each other in modularity literature, our findings suggest that they may crow out each other and are rather difficult to combine. Cars are not nearly decomposable in nature, and OEMs have to specifically invest in the components knowledge to achieve higher levels of modularity.

These findings also suggest why modularity may still have a limited traction in the automotive industry (Camuffo, 2004; Fourcade and Midler, 2004; MacDuffie, 2008): a) carmakers, to increase vehicle components modularisation, need to heavily invest in components specific knowledge. Modularity and design outsourcing work as substitutes and are rather difficult to combine thus b) carmakers modularise only strategically relevant components. Moreover c) cars components share a number of interfaces that, once frozen, might negatively affect the introduction of innovations and/or new car styles.

These findings have straightforward managerial implications. On one side, high levels of component modularity require specific investments and should be carefully driven by the firm's strategy. Modularity may constraint the supplier's innovative contribute, but can also increase the control over the component performances and the supplier's substitutability. On the other side, low levels of component modularity can reduce the investments in the component specific knowledge by the OEM and increase the openness to supplier's innovations. The drawback is the OEM's need to ensure the control over the component via complex inter-organizational procedures.

All the main findings contained in this work might be further developed and disentangled as concerns both the car industry and other settings. In fact, even if this study is industry specific, since some of the cars features, as their complexity, belong to other products, as aircrafts, this study might offer a new grid to analyze the appropriateness of modular strategies in other industry settings.

Finally, we recognize that the methodology employed might limit the generalizability of our results and that, even if we interviewed the supplier to respect the ceteris paribus conditions of the quasi-experimental deign, this work might be further improved interviewing the two carmakers in-order to further appreciate the role of modularity in the automotive industry, and the complexities of its definition process.

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Table 1. List and duration of interviews at Denso

DNTS interviewees	**Duration**	**# interviews**
R&D chief	4h30min	3
R&D chief for Alpha	2h30min	1
R&D chief for Alpha assistant	3h30 min	2
R&D chief for Beta	3h30min	2
Sales & marketing manager for Alpha	2h	2
Sales & marketing manager for Beta	2h	2
Total	**18h**	**12**

Table 2. Interfaces analysis of the Project-A A/C system

The table employs a modified version of the Design Structure Matrix to analyze the interfaces between the Project A A/C system and the other car's components with which it interacts.

	Air conditioning system															
	Spatial Interfaces				Informative Interfaces				Energetic Interfaces				Material Interfaces			
Car's components	O-S	C-S	N-S	Stability	O-S	C-S	N-S	Stability	O-S	C-S	N-S	Stability	O-S	C-S	N-S	Stability
Engine cooling system			x	5					x			5		x		5
Frigorific circuit			x	5					x			5	x			5
Electrical box			x	5	x			5	x			5	x			5
Flame damper			x	5												
Instrument panel (shape)			x	5					x			5			x	5
Instrument panel (mechanics)			x	5						x		5				
Crossbar			x	5					x			5				

O-S= open-standard interface; C-S= closed standard interface; N-S= non-standard interface

The interfaces stability is measured employing a 1-5 scale where 5 stands for "frozen interface" and 1 stands for "unstable interface".

Table 3. Interfaces analysis of the Project B A/C system

The table employs a modified version of the Design Structure Matrix to analyze the interfaces between the Project A A/C system and the car's components with which it interacts.

	Air conditioning system															
	Spatial Interfaces				Informative Interfaces				Energetic Interfaces				Material Interfaces			
Car's components	O-S	C-S	N-S	Stability	O-S	C-S	N_S	Stability	O-S	C-S	N-S	Stability	O-S	C-S	N-S	Stability
Engine cooling system	x			5					x			4	x			5
Frigorific circuit	x			5					x			5	x			5
Electrical box		x		3		x		4		x		5		x		5
Flame damper		x		5						x		2	x			5
Instrument panel (shape)		x		3						x		3			x	1
Instrument panel (mechanics)		x		3		x		2		x		3			x	1
Crossbar		x		3						x		3			x	1

O-S= open-standard interface; C-S= closed standard interface; N-S= non-standard interface.

The interfaces stability is measured employing a 1-5 scale where 5 stands for "frozen interface" and 1 stands for "unstable interface".

Figure 1. **ALPHA approach in defining the A/C system architecture**

The main rectangle delimited by the green frame represents the A/C system interfaces, the small rectangles represent the inner A/C system sub-components, and the oval the overall performance parameters and engineering solutions. ALPHA fully specified all the interfaces (the green zone), some active components (the blue boxes inside the A/C system boundaries), and the performance parameters (the yellow zones). The white zones were those fully managed by DNTS.

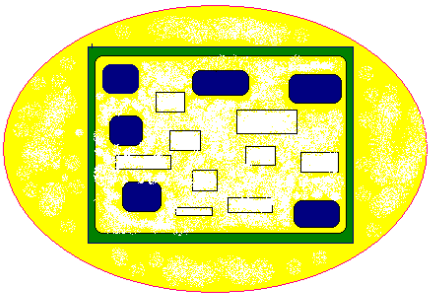

Figure 2. BETA approach to the A/C system co-development with DNTS.

The main rectangle delimited by the green frame represents the A/C system interfaces, the small rectangles represent the inner A/C system sub-components, and the big oval the overall performance parameters and engineering solutions. BETA sets the A/C system main concept and architecture with the help of DNTS (the yellow zone). Also, BETA co-develops the interfaces with DNTS (the green zone) and does not define the A/C system inner components (there is no blue box inside the A/C system boundaries).